

Discovery deep space optical communications (DSOC) transceiver

W. Thomas Roberts

Jet Propulsion Laboratory, The California Institute of Technology¹

ABSTRACT

NASA's 22 cm diameter Deep Space Optical Communications (DSOC) Transceiver is designed to provide a bi-directional optical link between a spacecraft in the inner solar system and an Earth-based optical ground station. This design, optimized for operation across a wide range of illumination conditions, is focused on minimizing blinding from stray light, and providing reliable, accurate attitude information to point its narrow communication beam accurately to the future location of the ground terminal. Though our transceiver will transmit in the 1550 nm waveband and receive in the 1064 nm waveband, the system design relies heavily on reflective optical elements, extending flexibility to be modified for use at different wavebands. The design makes use of common path propagation among transmit, receive and pointing verification optical channels to maintain precise alignment among its components, and to naturally correct for element misalignment resulting from launch or thermal element perturbations. This paper presents the results of trade studies showing the evolution of the design, unique operational characteristics of the design, elements that help to maintain minimal stray light contamination, and preliminary results from development and initial testing of a functional aluminum test model.

Keywords: DSOC, Deep Space Optical Communications, Laser Communications, Discovery Mission Communications

1. INTRODUCTION

NASA's commitment to extending space communications capabilities into the optical portion of the electromagnetic spectrum has been boosted in recent years by the highly successful Lunar Laser Communications Demonstration (LLCD) mission¹ in which high rate optical communications between ground stations on earth and the LLST terminal on the LADEE spacecraft in orbit about the moon were demonstrated². NASA has extended this concept to supporting a high bandwidth optical relay system, the Laser Communications Relay Demonstration (LCRD), on which multiple optical ground stations will demonstrate high bandwidth networking operations through a pair of optical terminals on board the STPSat 6 geostationary satellite^{3,4}.

In 2014, NASA announced an incentivized opportunity to carry the Deep Space Optical Communications (DSOC) Flight Laser Transceiver on board one of the Discovery missions proposed to fly around year 2021. Of the five Discovery proposals selected in 2015 to move on to the second phase of development, three (NEOCam, Psyche and Veritas) proposed to use the DSOC transceiver to demonstrate high-rate data return from deep space to an optical telescope on Earth. Recent announcements indicate that the Psyche mission concept has been selected, though details about the flight opportunity are still forthcoming.

2. DESIGN CONSIDERATIONS AND OBJECTIVES

The DSOC Optical Transceiver Assembly is designed to perform three essential functions, central to the beacon-dependent operations concept:

- (1) Receiving, identifying and determining the angular location of an Earth-based beacon
- (2) Transmitting the downlink data signal to a calculated point-ahead location (pointing the signal to the predicted location of the earth-based ground station once the signal from the transceiver reaches earth, and,
- (3) Observing a faint reference image of the downlink signal to verify the offset and direction of the downlink pointing relative to the observed uplink. This reference signal is used to provide fine adjustment to the pointing of the downlink signal.

¹ This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

The design of the system must accomplish these functions with the minimum use of resources (mass, volume and power) that are always so dear on deep space missions. Achieving these functions requires special attention to two particular concerns: stray light and thermal distortion.

2.1 Stray Light Suppression

Deep space optical communications is, in part, feasible and efficient because of the narrow beam widths (~ 10 microradian) achievable from sub-meter apertures using wavelengths on the order of 1 micron. However, with that advantage comes the difficulty of maintaining sub-microradian pointing of these narrow beams. To achieve that, the DSOC system uses a kilowatt-class laser beacon transmitted from earth, to be received and imaged by the DOSC transceiver as a pointing reference. Using this reference, and the known translational and rotational velocities of Earth, the DSOC flight transceiver calculates the offset angle to which it must point (the point-ahead angle) such that the communications beam will be centered near the ground receive aperture when the signal from the spacecraft gets back to Earth. However, even a kW class beacon transmitted from Earth in a 40 microradian beam to a 22-cm aperture at a distance of just half an Astronomical Unit (AU) provides at best about 5×10^7 photons/second. By contrast, solar illumination of the aperture a distance of 1.5 AU from the Sun can be about 9 orders of magnitude greater in a 1 nm band. Thus, even apparently minor sources of stray light can have profound implications for our ability to observe the beacon, much less accurately centroid.

2.2 Differential Thermal Loading

In deep space, maintaining diffraction-limited performance of the transceiver assembly is a significant concern. The transceiver does not have the luxury of being in a thermally stable condition. At some times, it may be pointed near the Sun, while at other times it may be pointed away from the Sun. In almost all cases, the side facing away from the sun will tend to radiate to deep space, and thus cool, without the beneficial warming of emission from nearby bodies or the atmospheric convective heat transfer of terrestrial systems. To a great extent, these thermal concerns can be ameliorated by enclosing the transceiver in multi-layer insulation (MLI); however, the opening of the main baffle tube and the primary mirror must be kept clear, and are thus still subject to conditions in which they absorb heat from the Sun or radiate to deep space.

The transceiver must maintain its functional performance under both conditions, affording little more than 1 dB of wavefront error loss for the aggregate system. Analytical modeling (Figure 1) shows that some of the most challenging conditions result from partial solar illumination of the primary mirror, setting up a thermal gradient across the mirror, and causing a differential thermal expansion of the element resulting in dozens of microradians of pointing error.

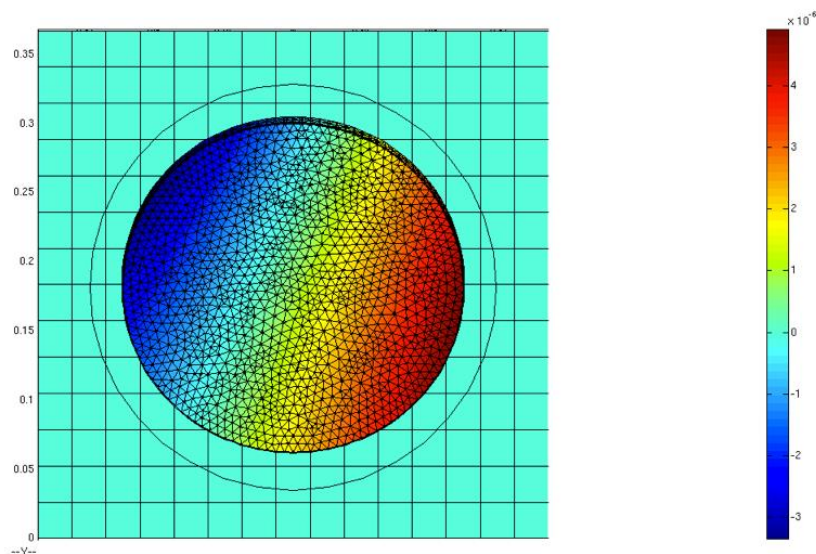


Figure 1. An analytical model (CIELO) of the thermal expansion of the primary mirror in Aluminum from partial illumination (right side) of the primary mirror by sunlight.

3. GENERAL OVERVIEW AND DESCRIPTION OF THE OPTICAL TRANSCEIVER ASSEMBLY

The Deep Space Optical Communications Program will develop an optical communications transceiver to facilitate laser communications with earth-based receivers from Deep Space. The project has developed a conceptual design called the Flight Laser Transceiver (FLT) comprised of a Floating Platform (FP) and a Stationary Platform (SP).

A diagram of an early concept of the OTA attached to the Isolation and Pointing Assembly (IPA) is shown below in lavender. The OTA provides the optics and optical baffling and acts as an interface and support platform for integrating all other components of the FP, including the Floating Platform Electronics (FPE), the Fiber Laser Collimator Assembly (COL), the Point Ahead Mirror Assembly (PAM), and the Camera. The OTA attaches via a set of monopods and bipods (TBR) to the other element of the FP, the Isolation and Pointing Assembly (IPA).

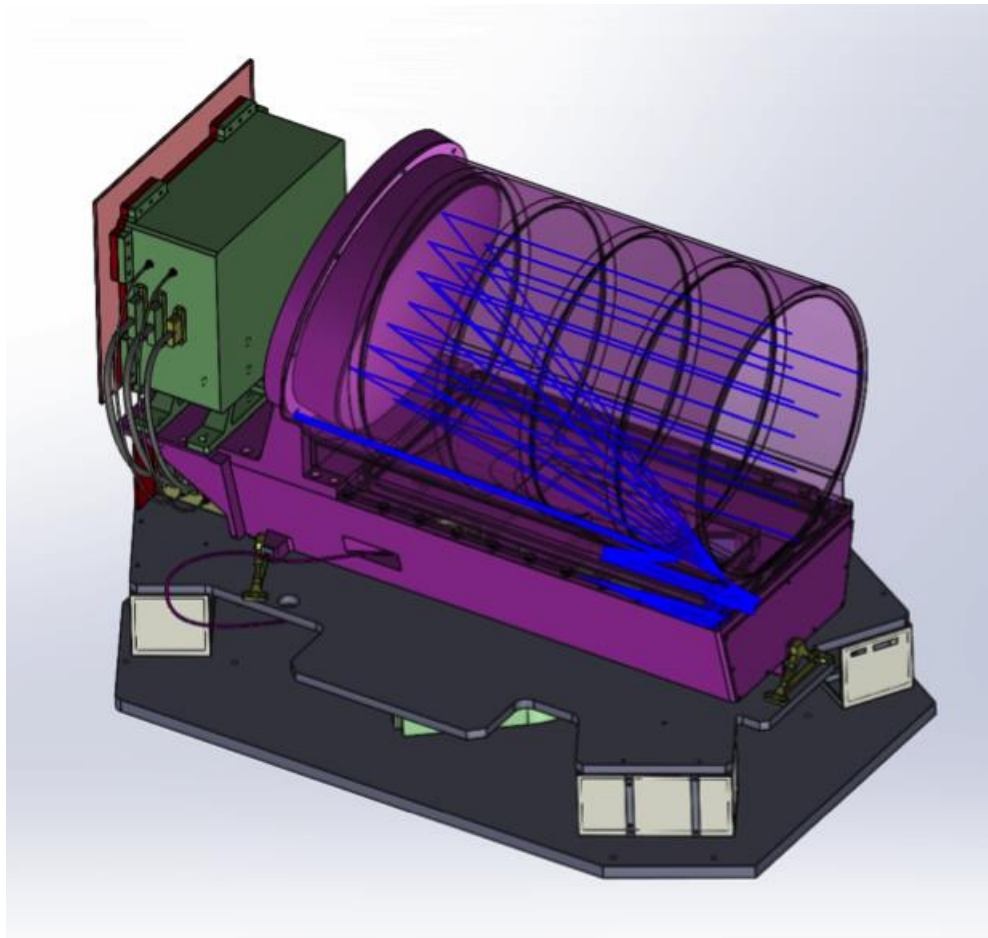


Figure 2. The DSOC Optical Transceiver Assembly (OTA in lavender) with the Floating Platform Electronics (FPE in green), Camera (in tan) attached to the Isolation and Pointing assembly (IPA in grey).

To accomplish the primary functions, subsets of components (shown in green) of the OTA must work in concert with one another. The primary components of the OTA consist of the following:

(1) An afocal, off-axis Gregorian telescope (M1, M2 and Gregorian field stop) which acts as an 11:1 beam expander/reducer;

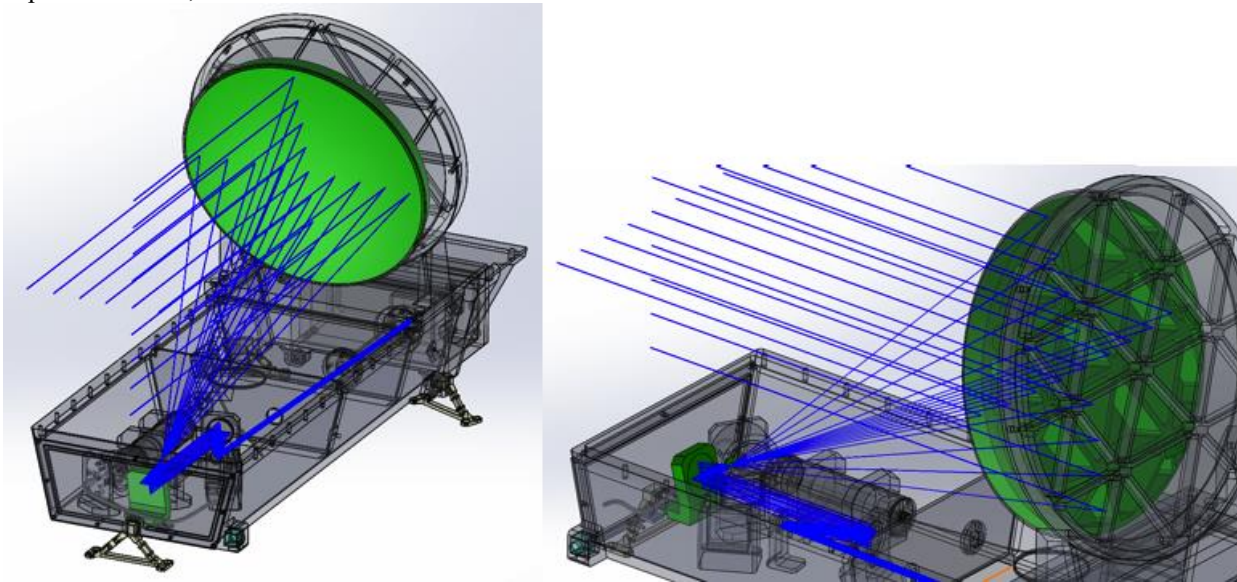


Figure 3 a and b. The afocal Gregorian telescope includes two off-axis parabolic mirrors (M1 and M2) as well as a Field Stop (not shown) at the focus of the primary mirror.

(2) A focusing classical Cassegrain telescope (M3 and M4) for generating images on the camera array;

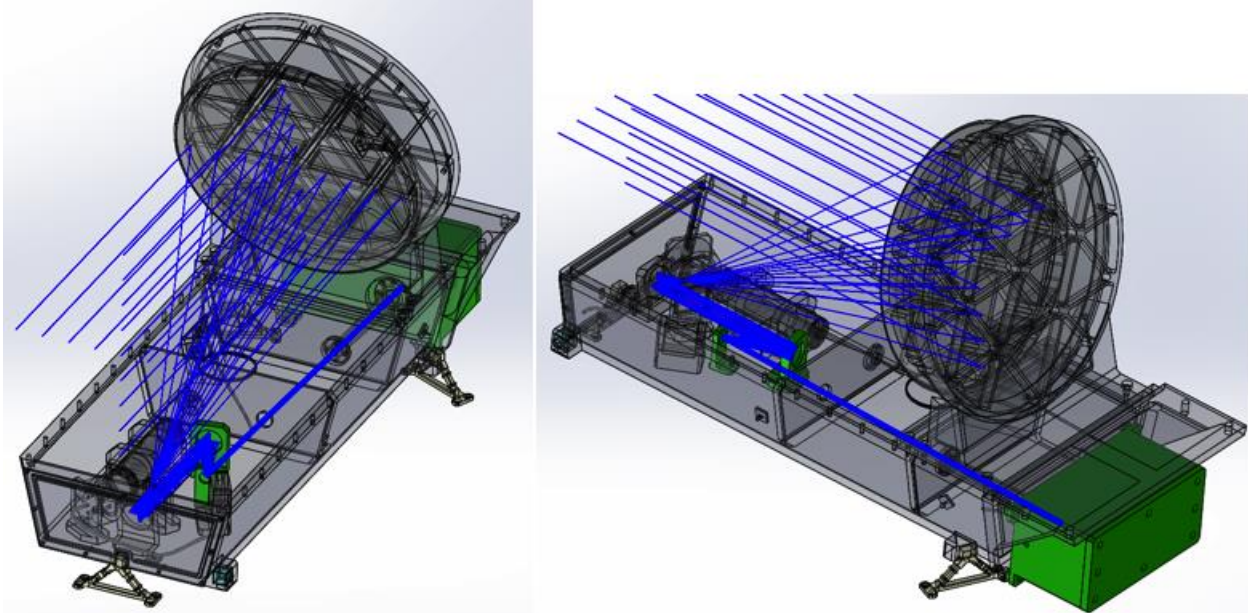


Figure 4 a and b. The focusing Cassegrain telescope includes an off-axis parabolic mirror (M3) and an off-axis hyperbolic mirror (M4). The Photon Counting Camera is highlighted in green as well.

(3) A dichroic beam splitter to separate the uplink beacon light from the downlink laser light;

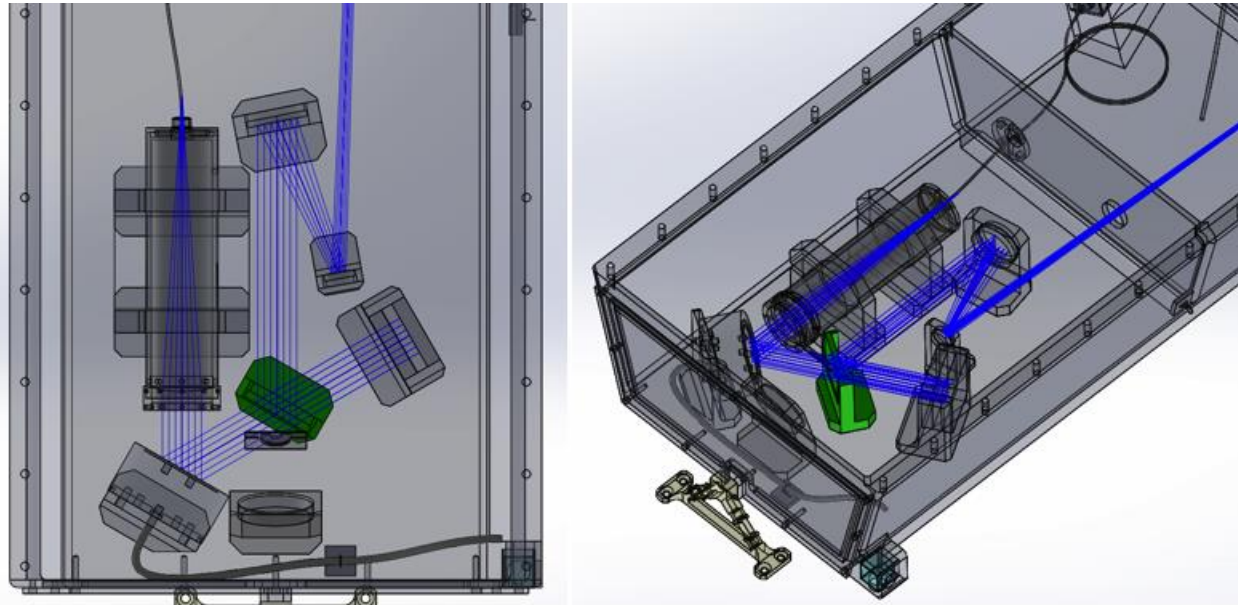


Figure 5 a and b. The dichroic beamsplitter, highlighted in green, is used in both transmit and receive channels.

(4) A retro-mirror component to attenuate and re-direct downlink beam light leaking through the dichroic beam splitter into the receive channel for registration on the PCC;

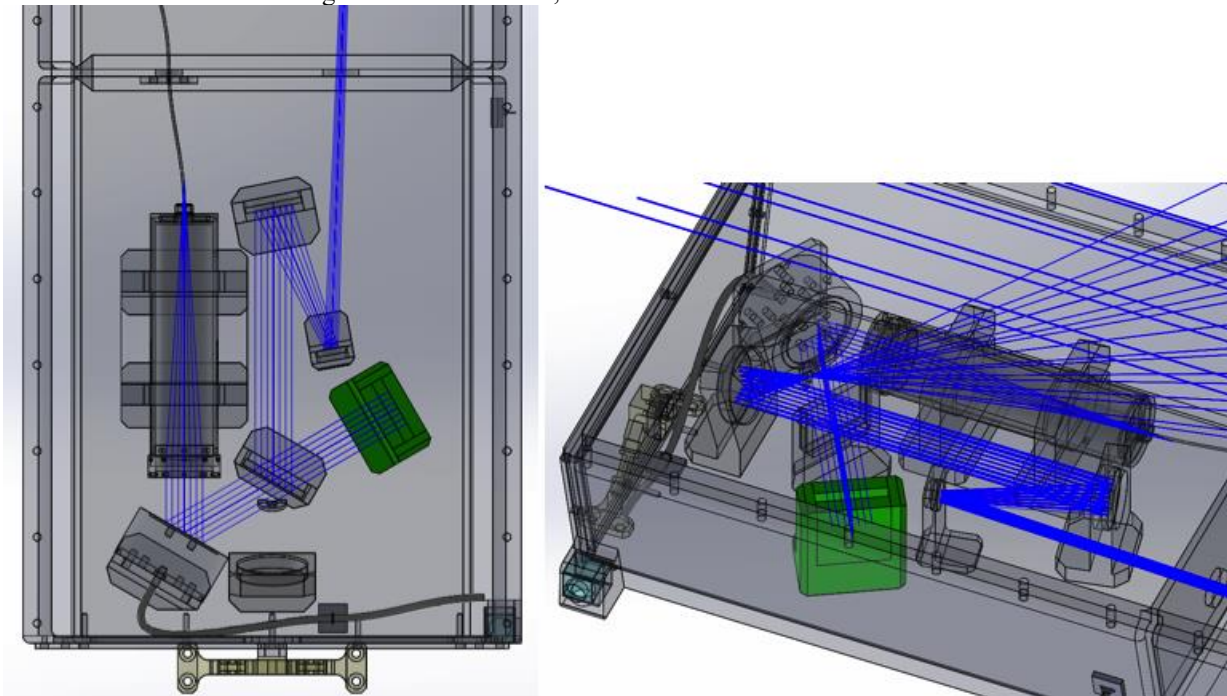


Figure 6 a and b.: The retro mirror assembly is composed of a mirror, two neutral density filters, and a mount.

(5) A narrow-band filter component, which provides additional baffling and houses a narrowband filter which spectrally limits background light on the Camera;

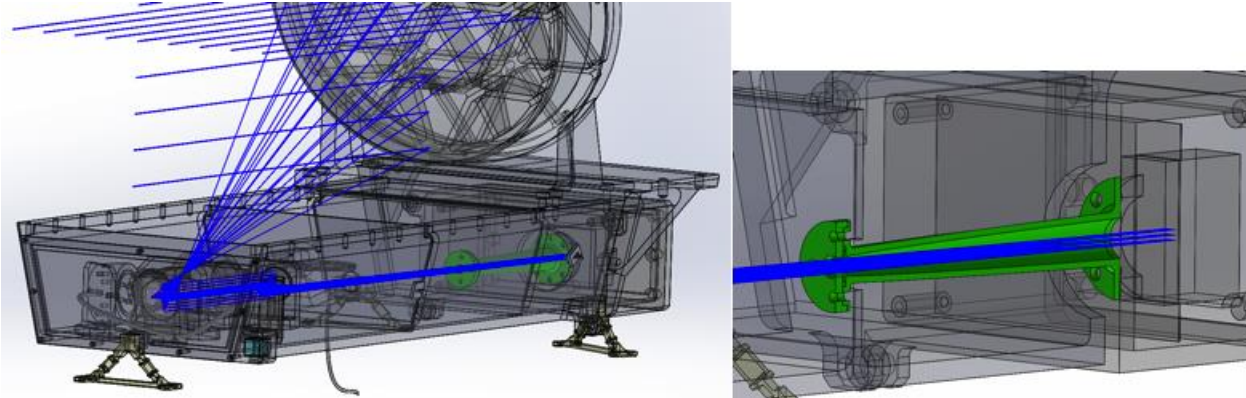


Figure 7 a and b.: The Camera baffle limits light to detector and houses a narrowband filter. Figure 7b is shown in cutaway view.

(6) An optical bench, which supports the optical components and holds them in alignment relative to one another;

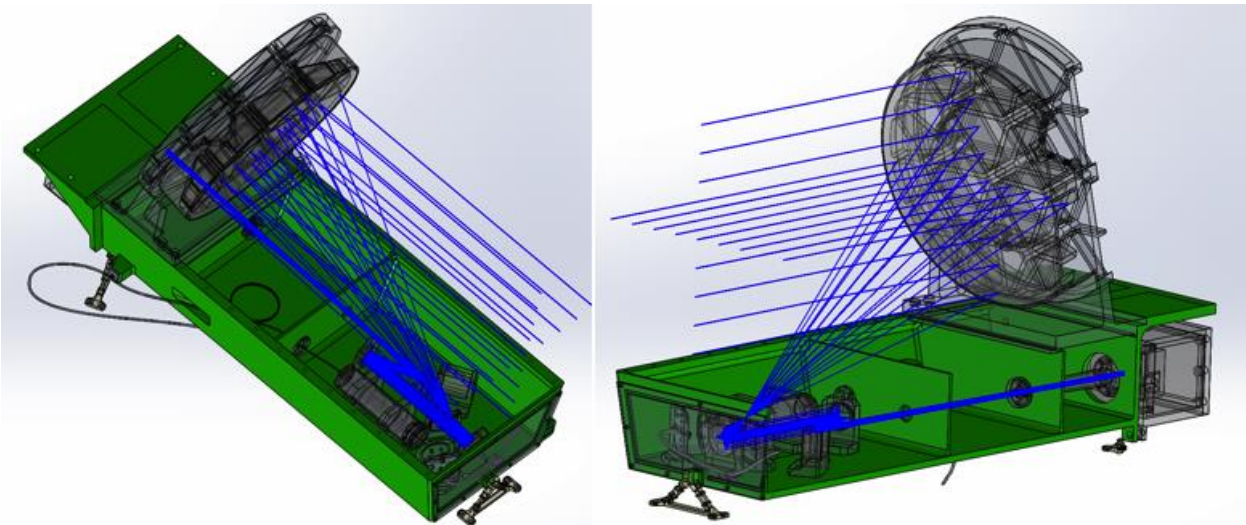


Figure 8 a and b. The optical bench integrated into OTA. Figure 8b is shown in cutaway view.

(7) A baffle top plate which houses the Gregorian field stop, limits stray light into the lower optical compartments, and manages the thermal loads on M1; and

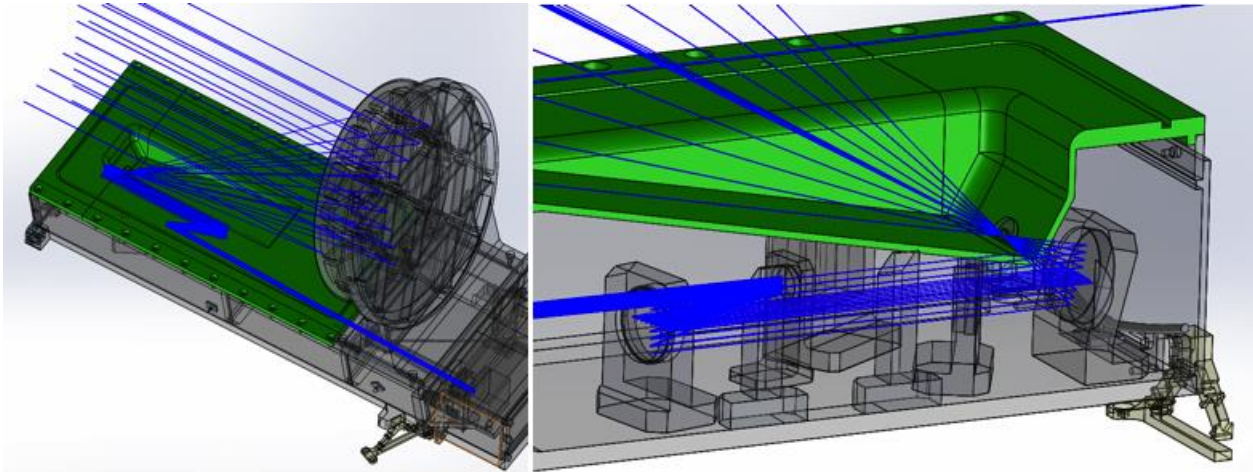


Figure 9 a and b. Baffle top plate serves as a mount for the Gregorian field stop. Concept shown here is a 2-piece top plate, with the fore plate remaining in place when aft plate is removed. This prevents the need to realign stop when accessibility to bench is needed. Both figures shown in cutaway view.

(8) A Stray Light Shield to be attached to the optical bench, which shields the primary mirror from off-axis illumination and assists with thermal management and protection of M1.

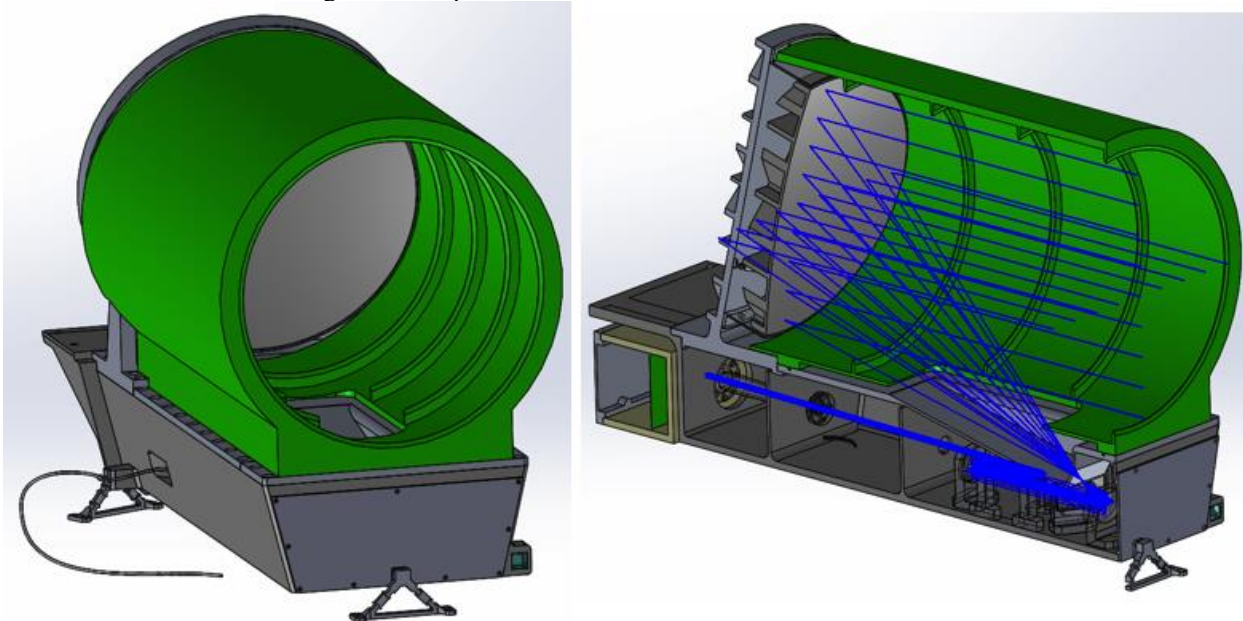


Figure 10 a and b. Stray Light Shield (SLS) mounted to the top of the baffle top plate. Figure 10b is shown in cutaway.

The Optical Transceiver Assembly hosts three main channels to support the previously-defined functionality; a receive channel, a transmit channel and a retro channel. Each of these channels uses a subset of the identified optical components as shown in Table 2.3-1:

Table 1: Optical Transceiver Channels

Sub-Assembly	Receive	Transmit	Retro
Afocal Gregorian Telescope	X	X	
Focusing Cassegrain Telescope	X		X
Dichroic Beam Splitter	X	X	X
Laser Collimator		X	X
Point Ahead Mirror		X	X
Retro Mirror			X
Narrow-band filter	X		X

3.1 Receive Channel

The receive channel accepts light from an earth-based beacon transmitting at 1064 nm, using the afocal Gregorian telescope to collect and concentrate the uplink beacon light, and to feed the collimated output beam through the dichroic beam splitter. The beam then enters the off-axis Cassegrain telescope, which focuses the light onto the Photon Counting Camera. The spot generated on the Photon Counting Camera serves as a pointing reference for the Isolation and Pointing Assembly.

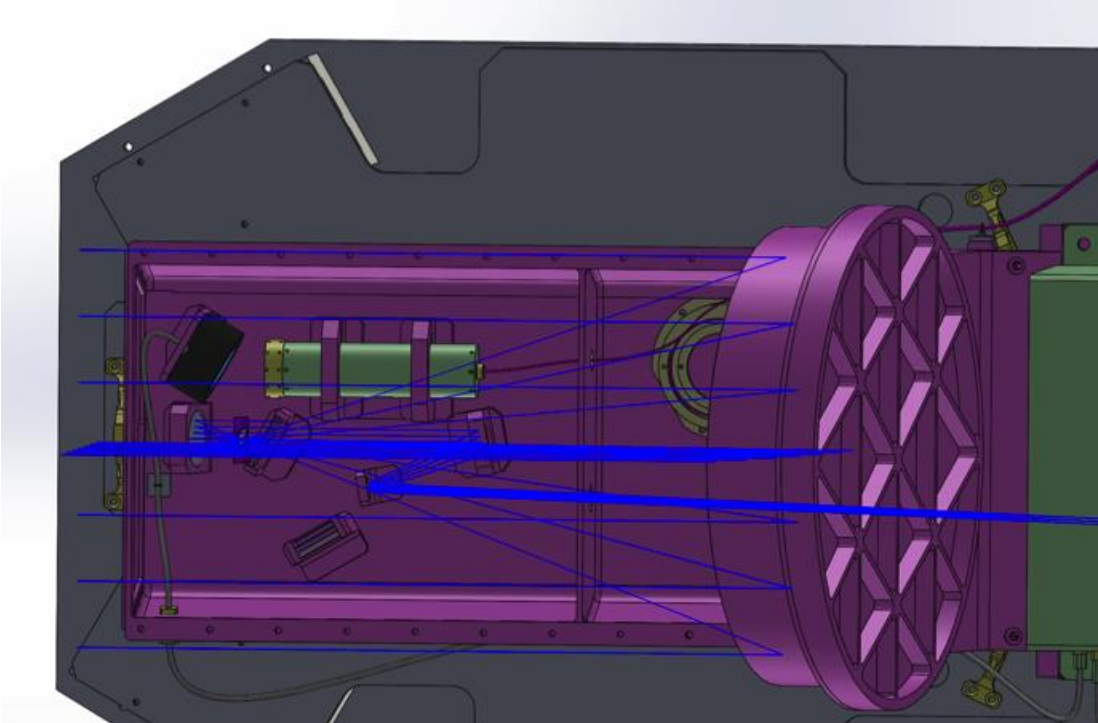


Figure 21. OTA Receive Channel showing the path from the external beacon source through the primary Gregorian telescope, to the camera array on the right.

3.2 Transmit Channel

The transmit channel, operating at 1550 nm, collimates light from the single-mode laser fiber, reflecting it off the Point-Ahead Mirror, which introduces the beam point-ahead angle. This light then almost completely ($\geq 99.8\%$) reflects from the dichroic mirror, directing it into the afocal Gregorian telescope, which acts as a beam expander to enlarge the beam and narrow its far-field divergence.

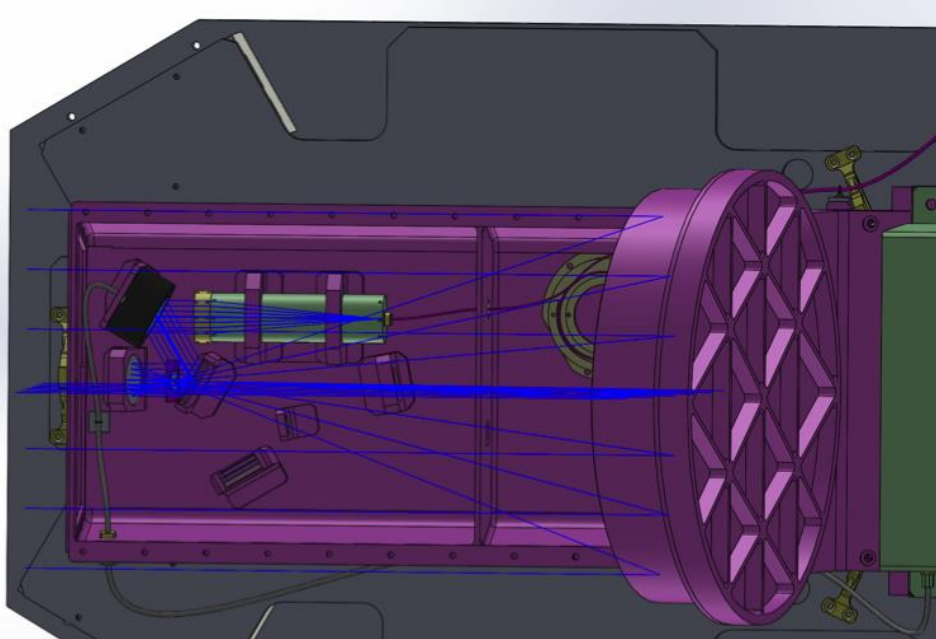


Figure 12. OTA Transmit Channel path from the laser collimator (green), reflections from the point-ahead mirror and the dichroic beam splitter, into the secondary mirror of the main telescope, and out of the front aperture of the system.

3.3 Retro Channel

The retro channel (also at 1550 nm) uses the residual transmit beam leaking through the dichroic beam splitter, reflecting it back into the latter portion of the receive channel path. The light is focused on the camera, and serves as a pointing reference to verify the correct point-ahead offset relative to the observed uplink beacon spot. The retro beam will be aligned with a static offset to avoid overlap and confusion between the uplink reference spot and the point-ahead spot.

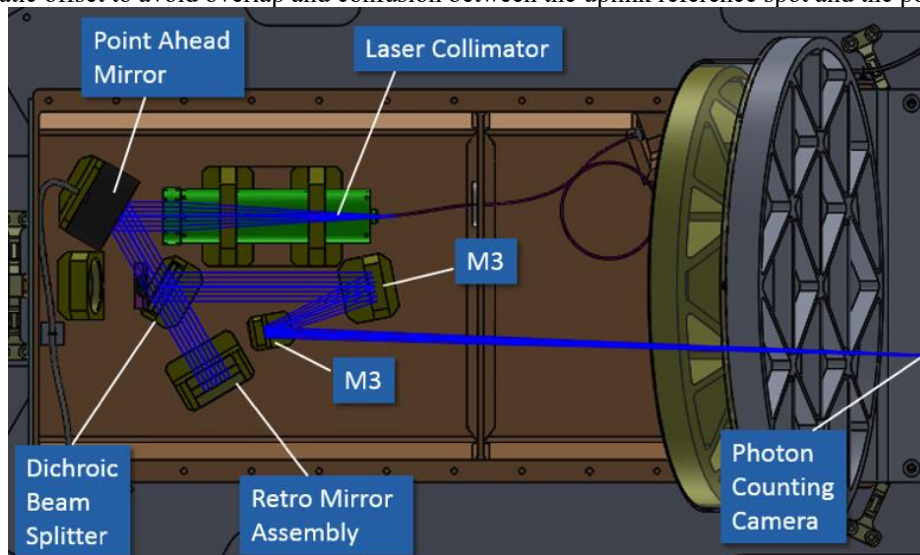


Figure 13. OTA Retro Channel trace from the collimator through the dichroic beam splitter onto the retro mirror. The retro-mirror reflects back to the dichroic beam splitter, which reflects into the receive path, ultimately producing a reference spot on the camera.

4. ADVANTAGES OF THIS DESIGN

4.1 Gregorian Fore-telescope design advantages

Other space optical communication system designs frequently use on-axis telescopes, particularly Ritchey-Chretien and classical Cassegrain designs. Such telescopes are efficient in their use of space, and generally will have a lower mass than an equivalent Gregorian telescope as a result of using a shorter baffle and metering structure. However, the stray light performance of the Gregorian telescope, which allows placement of a field stop immediately after the primary mirror, constitutes such an inherent advantage as to tilt the trade towards the Gregorian design.

Below near-sun pointing angles of about 4 degrees, Cassegrain type telescopes suffer from scattering not only from the primary mirror, but also introduce scattering from the secondary mirror as rays directly reflected from the primary concentrate on and are scattered from the secondary mirror. Though rays reflected from the secondary mirror from the off-axis Sun will generally be intercepted by other elements of the system, scattered rays from the secondary cannot be limited either by the use of field stops or Lyot stops. That scattered light has a clear path to the focal plane.

The problem of scattered light from the secondary can be worse than the scattering from the primary because the secondary mirror is optically much closer to the focal plane than the primary mirror. In the DSOC design the solid angle subtended by the focal plane array as viewed by the secondary mirror is almost 100 times the solid angle as viewed through the secondary mirror from the primary mirror surface. In a comparable Cassegrain design, in cases in which concentrated light from the primary illuminates the secondary mirror, the secondary mirror quickly becomes the dominant scattering source.

The longer track of the Gregorian telescope is not all bad; it allows the primary mirror, the only optical element that normally has any potential for direct solar illumination, to be situated at the back of the tube of the stray light shield. This is advantageous in that the longer tube shades the primary mirror more and to lower angles than a shorter shade would. Furthermore, it also admits a smaller solid angle for contaminants on the primary mirror, thus keeping the contamination-induced scatter low for a longer period of time.

Finally, the field stop can be made so small that it can limit the light introduced into the aft optics, protecting the optics and camera array from damage in the event of accidental direct-Sun pointing. The field stop need only be large enough to admit the focused light moving in both directions between the primary and secondary mirrors. For most communications situations of interest, a field of 1 mrad is sufficient to accommodate point-ahead angles, including alignment margins. Considering that the Sun from Earth subtends over 9 mrad, this means that less than 2 percent of the direct solar illumination would be passed on through the field stop, even in the event of direct Sun pointing. The rest would be mostly reflected back toward the primary mirror for return to the outside environment.

4.2 Off-axis design advantages

The off-axis telescope design leads to several advantages. Most obvious is that, for a transmitted narrow Gaussian beam, the full aperture of the telescope should be used. The peak irradiance of the Gaussian (twice the average power density found in the $1/e^2$ -described circle) is at the center of the beam. A Cassegrain-type design places a secondary mirror obscuration there, resulting in about a 0.4 dB loss in the far field for a 20% linear obscurations.

Similarly, a loss of received beacon power would accrue proportional to the area lost from the on-axis obscuration. Thus a 20% linear obscuration, would introduce a small, but noticeable, 4% loss of received power from a weak beacon.

Another advantage of an off-axis system is that the diffraction and scattering from a secondary obscuration and support spider are eliminated altogether. This simplifies the manufacture and alignment of a Lyot stop further back in the system, which only needs to mask glints from the edge of the aperture.

A major advantage in stray light reduction result from the use of an off-axis Gregorian, in which case the secondary mirror is on the opposite side of the optical axis from the primary mirror. This allows the near-complete closure of all optical elements after the primary mirror in an aft-optics chamber, for which the only entrance point for stray light is the field stop. Given that the field stop is roughly 0.4 mm², there is little opportunity for stray light to enter the chamber.

4.3 Mono-material design

The system is designed so most optically-relevant materials (powered mirrors, metering structures, optical mounts) are made of the same material with an isotropic coefficient of thermal expansion. This restriction assures that the system remains aligned under ‘soak’ temperature changes, in which all elements are in thermal equilibrium with one another. Even though thermal expansion of, for example, the primary mirror would change its effective focal length linearly with temperature, the optical bench made of the same material would increase by the same linear factor, as would the focal length of the secondary mirror. This, it becomes, in effect, a scale change, but focal ratios remain constant and the system remains aligned.

4.4 Three-channel design

The three channels of the design are arranged such that almost all optical elements are common to two of the channels, resulting in a self-correcting system. For example, should the pointing of the primary mirror go askew, either from launch vibration or thermal misalignment, the apparent location of the upwelling reference beacon on the detector array will be displaced. However, since the downlink beam also goes through this element, it will likewise be mispointed in the same direction, by the same amount, correcting the error without intervention. Similarly, should the aft telescope that focuses the collimated beam from the secondary mirror on the camera be misaligned, the reference spot generated by the retro-channel will be equally misaligned, causing a correction to be introduced into the point-ahead mirror to bring pointing back to the intended location. The only optical element which does not currently have this feature is the retro-mirror itself, though we are considering a means of eliminating pointing errors in this element as well.

5. MODELED STRAY LIGHT PERFORMANCE

Analysis of the stray light performance of the system under conditions simulating the performance of the OTA in orbit about Earth was conducted by Breault Research Organization. Under worst case conditions (the telescope pointing to within 3 degrees of the limb of the Sun, allowing full, direct, low-angle illumination of the primary mirror) the modeled flux at the focal plane array was 2.5×10^{-6} Watts/mm² for every Watt/mm² irradiance at the aperture. At a distance of 1.5 AU from the Sun, the expected solar irradiance is about 6.2×10^{-2} Watts/mm². Assuming a narrow-band filter with a 1 nm Noise Equivalent Bandwidth suppresses all but 0.05% of the solar spectral power, we find about 4×10^6 photons/pixel/sec incident at the focal plane, about 10% of what we expect to see with a 1 kW beacon at 0.5 AU.

Viewing the statistics of scattering paths into the focal plane shows that almost all of the scattering comes from direct scattering off the primary mirror. From this, we see that the only significant improvements to be made must come from making the primary mirror smoother or cleaner. Fortunately, this does not appear to be necessary.

Table 2 Fraction of scattered rays reaching the focal plane for each of the principal scattering paths

#	Path	Percent contribution	Running total
1	S --> Primary --> Det	99.3	99.3
2	S --> Floor --> Field stop edge --> Det	0.4	99.7
3	S --> Primary --> Narrow band filter --> Det	0.1	99.8
4	S --> Floor --> Primary --> Det	0.1	99.9

As the source of stray light (the Sun) moves farther afield, the point source transmission ratio gets smaller (Figure 14), confirming our expectation that the 3-degree near-Sun pointing was indeed the worst case. Scattered sunlight decreases as angle increases, so our ability to discern the beacon spot from background light continues to improve.

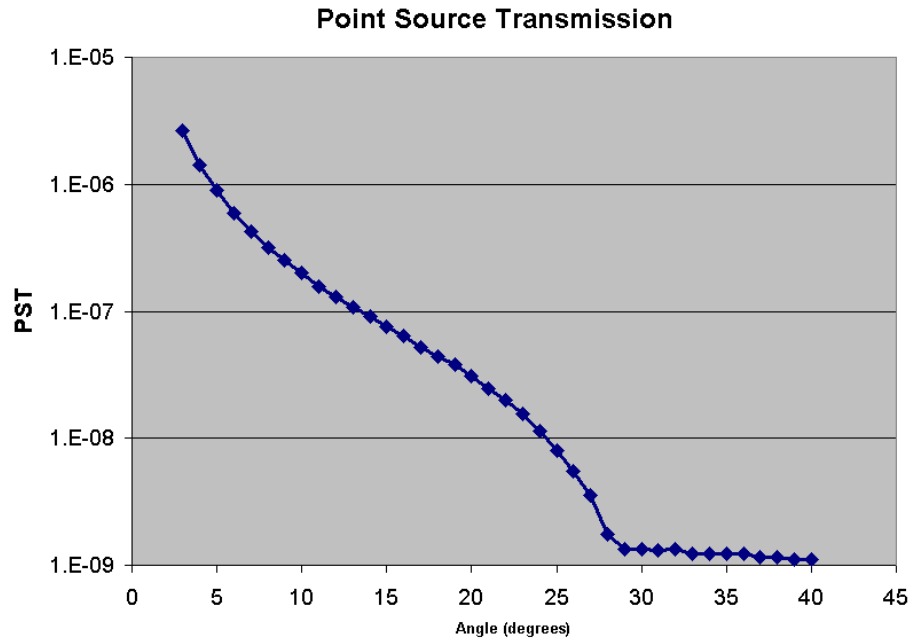


Figure 14. The point source transmission ratio is the predicted irradiance at the focal plane as a function of source irradiance at the aperture.

6. ALUMINUM TEST MODEL FABRICATION AND TESTING

A prototype of the Optical Transceiver Assembly was produced out of aluminum by Coherent, Inc. in Richmond, CA. To demonstrate operation of the DSOC transceiver under adverse illumination conditions, such as when supporting a communications link that requires pointing near the Sun, all mirrors were made with a proprietary process that achieved an RMS surface roughness of about 20 Angstroms (confirmed by AFM measurements). The prototype mirrors were coated with gold to support infrared testing.

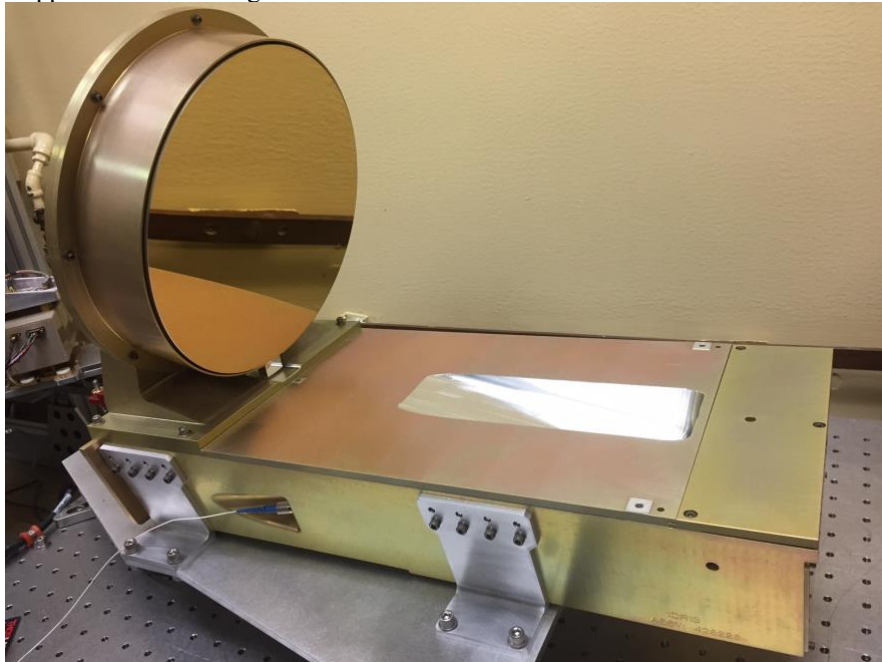


Figure 15. The all-aluminum OTA without the stray light shield, used for optical performance and concept validation testing.

To accommodate budget and schedule, several commercial off-the-shelf parts were used to populate the OTA. A Thorlabs short-pass beam splitter was used in the dichroic beam splitter assembly to efficiently transmit the 1064 nm uplink signal while reflecting the 1550 nm downlink. This mirror is nominally intended for use at a 45 degree angle of incidence, but analysis showed it would still have sufficient performance at the designed 30 degree AOI. A piezo-driven mirror assembly by Cedrat Technologies was used in the point-ahead mechanism(PAM), and a compact InGaAs camera from Sensors Unlimited (rather than the planned photon-counting camera) was used to image the optical spots. Finally, a custom collimator assembly from LightPath Technologies was used to collimate the beam emanating from the end of a remote 1550 nm laser source.

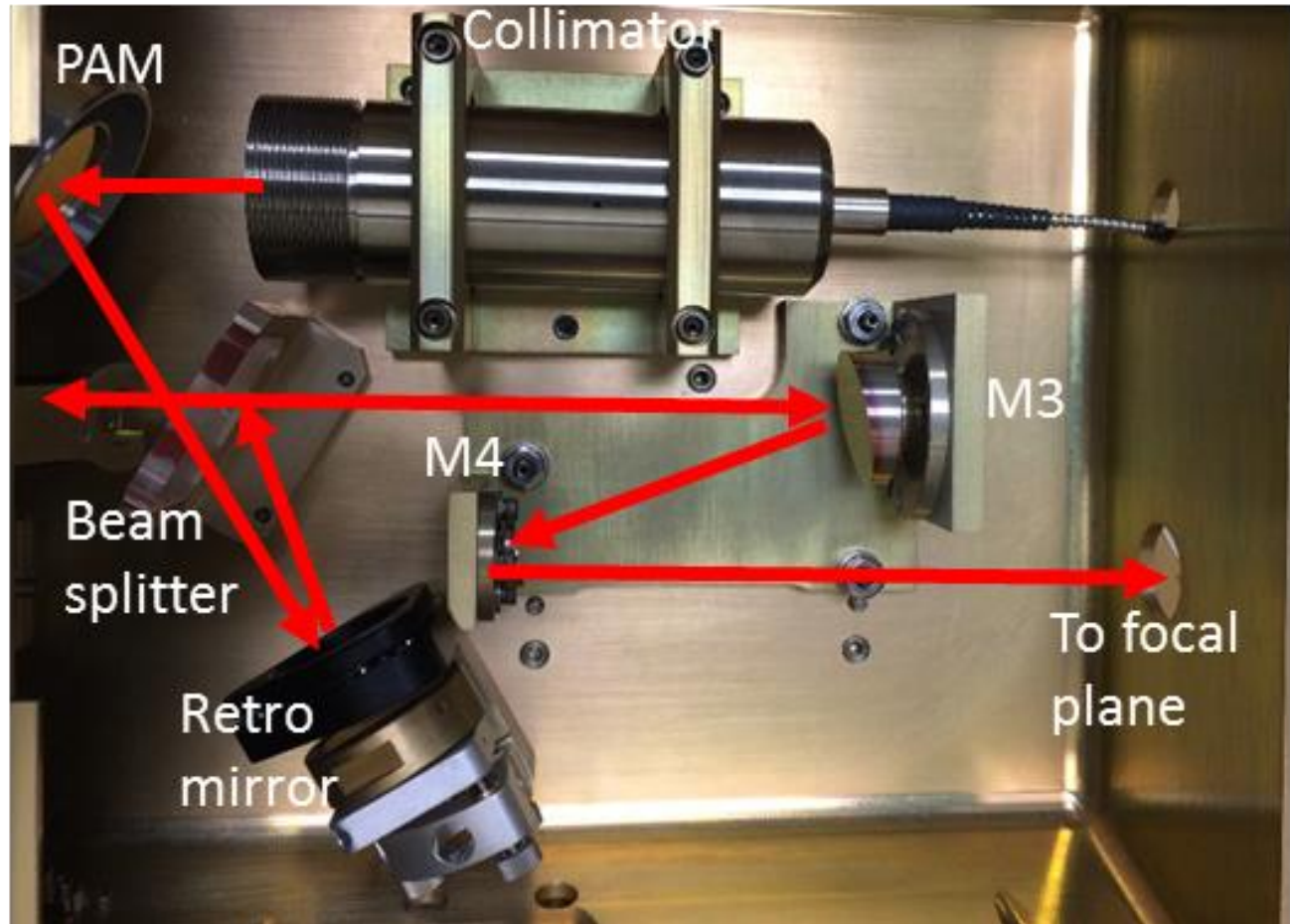


Figure 16 Internal optical elements showing the retro-beam path from the laser collimator to the photon counting camera.

The assembly was aligned, and placed on the Lasercom Test and Evaluation Station (LTES)^{6,7}, a system for optically characterizing laser communication systems. The initial test injected a collimated 1064 nm Gaussian beam into the aperture of the system to confirm alignment of the optics and the resulting wavefront quality of the system. The LTES aperture of 20 cm, smaller than the 22 cm clear aperture of the OTA, limited the resolution of the measurement. An image of the focused spot on the camera, representative of the received beacon spot used for identifying the ground station position, is shown in Figure 3. The first Airy ring is observable, and the 14 urad width of the Airy disk confirms the system performance is near the diffraction limit.

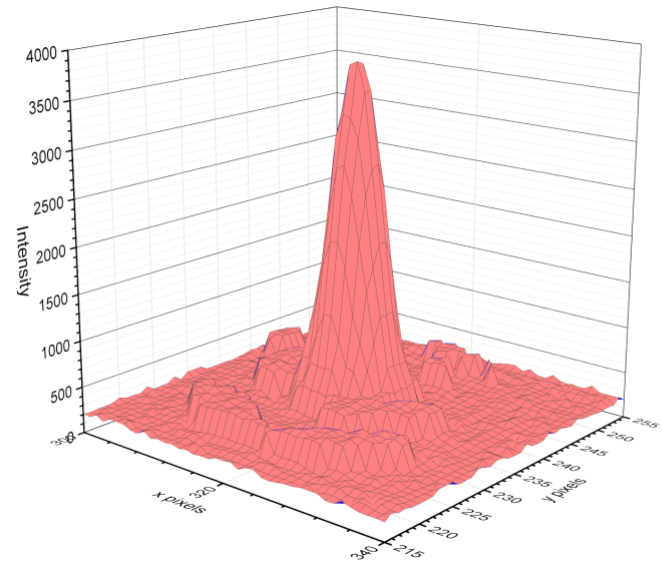
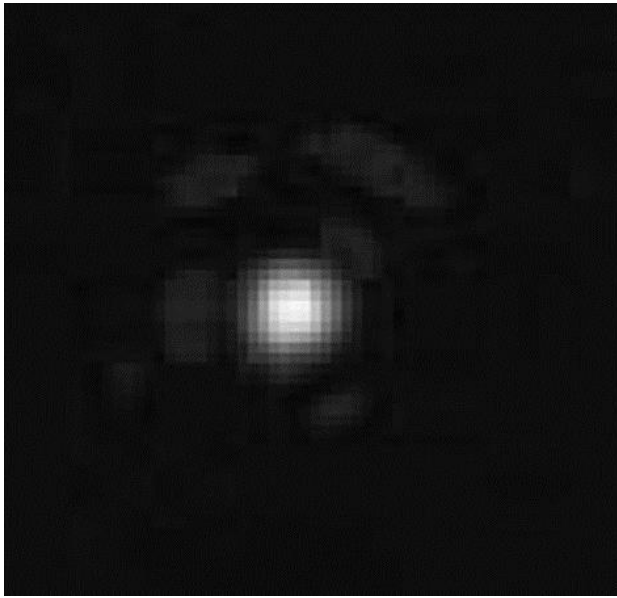


Figure 17. Near diffraction-limited spot image recorded by the Aluminum OTA.

Testing of the system performance and concept validation is currently under way.

7. SUMMARY

The DSOC Flight Laser Terminal's Optical Transceiver Assembly is designed to operate in the harsh environmental conditions expected to be found across the inner solar system. It incorporates channels for observing an uplink beacon from Earth to be used as a pointing reference, transmitting a diffraction-limited downlink beam back to the predicted location of the earth-based ground station when the signal arrives, and a reference channel for confirming accurate pointing of the downlink signal to the intended point-ahead location.

The design incorporates many features focused on eliminating stray light, and predictive modeling shows that it performs very well even, under harsh illumination conditions. We predict that any significant future improvements to stray light must come from producing a smoother primary mirror or improvements in maintaining optical cleanliness.

A test article was fabricated out of Aluminum, and initial testing shows that it achieves near-diffraction-limited performance on the uplink receive channel. More extensive testing on the other channels, and validation of the pointing concept is under way.

ACKNOWLEDGEMENTS

The author wishes to acknowledge colleagues Michael M. Borden for production of the CAD figures (2-13), Mike Chainyk for the CIELO modeling shown in Figure 1, Gary Peterson of Breault Research Organization for analysis and Figure 14, and Joseph Kovalik for preliminary test results and Figures 16-17.

REFERENCES

- [1] The Lunar Laser Communications Demonstration (LLCD), D. M. Boroson, J. J. Scozzafava, D. V. Murphy, B. S. Robinson, H. Shaw, IEEE Conference on Space Mission Challenge for Information Technology, 2009, pp. 23-28.
- [2] Overview and Results of the Lunar Laser Communication Demonstration, D. M. Boroson, B. S. Robinson, D. V. Murphy, D. A. Burianek, F. Khatri, J. M. Kovalik, Z. Sodnik and D. M. Cornwell, Proc. SPIE 8971, Free-Space Laser Communication Technologies XXVI, (March 6, 2014)
- [3] Overview of the Laser Communications Relay Demonstration, B. L. Edwards, D. Israel, K. Wilson and J. Moores,, Space Operations Conference (2012).
- [4] A Day in the Life of the Laser Communications Relay Demonstration Project, B. Edwards, D. Israel, A. Caroglanian, J. Spero, T. Roberts and J. Moores, Space Operations Conference (2016).
- [5] Optical Antenna Gain. 1: Transmitting Antennas, B. J. Klein and J. J. Degnan, Applied Optics, 13 no. 9, pp 2134-2141 (September 1974).
- [6] Lasercom test and evaluation station for flight terminal evaluation, K. E. Wilson, N. A. Page, A. Biswas, H. Hemmati, K. Masters, D. M. Erickson, J. R. Lesh, Proc SPIE 2990, Free-Space Laser Communication Technologies IX, 152 (April 24, 1997)
- [7] Lasercom test and evaluation station (LTES) development: an update, Proce. SPIE 3266, Free-Space Laser Communication Technologies X, 22 (May 27, 1998)